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ORIGINAL ARTICLE

Exploring sustainable heating solutions for buildings at the neighbourhood level

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Abstract Space heating in buildings represents nearly half of the final heat demand in Europe. The potential to save emissions from existing fossil-based heating supply systems is substantial. The Netherlands announced in 2018 its decision to phase out natural gas by 2050 and to supply buildings from 2021 with sustainable heating. Models with a high level of spatial resolution can support the assessment of potential low-carbon heating systems at the local level. This study introduces the *Vesta MAIS* model, an open-source tool developed for local governments and urban planners in the Netherlands to support the development of municipal roadmaps. The method presented in this study can be applied for a neighbourhood or city and provides new insights for Dutch local authorities and researchers on the suitability and limitations of the *Vesta MAIS* model. Four scenarios, including individual and district heating technologies and building shell improvements, are compared up to 2030 from a techno-economic and environmental perspective. Our results demonstrate that district heating appears to be the most suitable strategy for the studied area, but with subtle underlying differences in the optimal levels of network temperature, heat density and building insulation. A further investigation of the most favourable combination of these parameters, the use of local data, and the inclusion of additional criteria, next to costs and CO_2 emissions, is suggested to increase the practical use of model outcomes. This research serves as a showcase emphasizing the importance of a local analysis in the decision-making of potential heating strategies.

Keywords Low-carbon built environment · Local heat planning · Heating supply systems · District heating · Electrification

Abbreviations

ATES	Aquifer thermal energy storage
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
DH	District heating
HP(s)	Heat pump(s)
HT	High temperature
HTDH	High-temperature district heating
Ins A	Insulation to energy label A+
Ins B	Insulation to energy label B
LCOH	Levelized cost of heat
LT	Low temperature
LTDH	Low-temperature district heating
O&M	Operation and maintenance
OPEX	Operational expenditure

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Introduction

Heat demand accounts for the largest share of the final energy demand in the EU (Connolly, 2017). Consumption for space heating and cooling in the European residential sector represents nearly half of the final heating and cooling consumption (Kavvadias et al., 2019). While some countries such as Denmark, Finland, Slovenia and Bulgaria already employ a high share of renewable sources for heating the built environment, many EU countries use heating technologies predominantly based on fossil sources (Bertelsen & Mathiesen, 2020; Naef et al., 2019). The decarbonization of the heating sector has, therefore, been identified as a priority area to achieve climate goals (European Commission, 2016).

The Netherlands offers a good example of an EU country with a heating sector that is largely based on fossil energy: 90% of Dutch households use individual natural gas-fired boilers (EuroStat, 2020). The remaining residential building stock is connected to high-temperature district heating (HTDH) networks, which are largely based on combined heat and power (CHP) plants, using natural gas. Few newer district heating (DH) systems include waste incineration plants, biomass boilers and aquifer thermal energy storage (ATES). Electric systems such as heat pumps (HP) only provide 1% of the total heat demand (Segers et al., 2020). Being one of the countries with the smallest share of renewable energy for residential buildings of the EU (Naef et al., 2019), the potential towards a sustainable heating economy is unquestionable.

In 2019, the Dutch government presented a climate agreement where an additional reduction of 3.4 megatons of carbon emissions (on top of the baseline reduction in the absence of the climate agreement) is planned by 2030 for the built environment and carbon neutrality by 2050 (Ministry of Economic Affairs and Climate, 2019). As part of the agreement, and further motivated by the recent seismic activities provoked by natural gas extractions in the Northern region of the country, the Netherlands intends to phase out natural gas supply from all buildings by 2050. The provision of natural gas for new buildings is already prohibited. Yet, the current challenge lays on the decarbonization of the bulk of the existing building stock. To reach this ambitious target, efforts are needed from a variety of actors at different governance levels. Municipalities have been assigned an important role in heat planning and the development of alternative heating systems which are technically, economically and socially shaped by the local context. Dutch municipalities will have to outline before the end of 2021 a cohesive vision and long-term plan that identifies and compares potential heating technologies at the various neighbourhoods.

Literature review

This section presents relevant sources related to the low-carbon heating systems studied. This is followed by reviewing recent literature on urban energy models that are suitable for the neighbourhood scale and the identification of the research gap and aim of this work.

Alternative supply heating technologies and energy efficiency measures in buildings

There have been great advances in the last years in understanding the potential and impacts of alternative heating systems such as DH networks and heat pumps (HPs).

DH appears as a prominent option in dense urban areas due to the potential for energy savings and for integrating renewable sources. There are several comprehensive reviews studying the development of European DH networks from a market, technical, environmental and institutional perspective (Lake et al., 2017; Mazhar et al., 2018; UNEP, 2015; Werner, 2017). The project Heat Roadmap Europe and the EU Hotmaps project comprise heat mapping exercises and system analysis at EU and country level (Möller et al., 2019; Connolly et al., 2014; Connolly, 2017; Möller et al., 2018; The EU Hotmaps project n.d.). In countries with well-established DH markets such as those in the Scandinavian region, there is a growing interest to lower the temperature of the DH network to achieve higher efficiencies, a high share of renewables and a better integration with the power system (Kavvadias et al., 2019; Lund et al., 2018; Vandermeulen et al., 2018).

Another alternative heating technology that can bring significant energy and emissions savings is the

HP, either air, water and ground source based (Carroll et al., 2020; Hepbasli & Kalinci, 2009; Sarbu & Sebarchievici, 2014). These can be integrated in DH systems (David et al., 2017; Sayegh et al., 2018; Wang, 2018) or installed at the individual household level (Bianco et al., 2017; European Copper Institute, 2018; Staffell et al., 2012).

To manage peaks in heating systems, thermal energy storage is a key function and can reduce energy consumption, emissions and heating costs while increasing the overall efficiency of the system (Alva et al., 2018; Arce et al., 2011). Another widely shared method to reduce heat demand and emissions while enabling lower temperature supply sources is retrofitting buildings (de Feijter & van Vliet Bas, 2020; Felius et al., 2020; Zuhaib & Goggins, 2019).

Improving the building shell in the Netherlands has a great potential as an energy-saving option as the building stock is rather old (Filippidou, 2018; Lechtenböhmer & Schüring, 2011). Likewise, the adoption of alternative heat systems as DH networks and HP are still niche technologies in the Dutch context due to its mature and highly competitive natural gas market. In the Netherlands, the potential of DH is estimated to be 50% of the heat demand in 2050 (Hoogervorst, 2017). However, DH faces some challenges. The low energy consumption levels of new buildings and (deep) refurbishments of existing buildings can affect significantly the profitability of the DH business case (Magnusson, 2012). Also, finding appropriate production sites and the high initial investments are important barriers (Rismanchi, 2017). Another complexity of DH implementation in the Netherlands is the bad perception of DH by the consumers caused by the lack of transparency in the costs paid, the lack of flexibility to switch to another supplier (which is easy for electricity and gas, but not for heat), and doubts about the environmental performance of DH networks (Hoogervorst, 2017).

Models to assess heating technologies at the neighbourhood level

In order to understand the most suitable combination of heat systems for particular neighbourhoods, it is necessary to compare both potential centralized and individual supply heating technologies and the required building insulation. Energy models can support local heat planners during heat planning to perform this task.

Internationally, the growing interest in urban energy modelling among researchers, urban planners and local authorities has led to a great variety of tools and modelling techniques that are suitable for neighbourhood or district-scale. These models can be found in the literature also as neighbourhood, local and community models. Several comprehensive reviews of energy models suitable for buildings at district scale have been published in the last decade, assessing the available models from a variety of angles (Allegrini et al., 2015; Connolly et al., 2010; Huang et al., 2015; Kesicki & Ekins, 2012; Lyden et al., 2018; Mendes et al., 2011; Scheller & Bruckner, 2019; Vreenegoor et al., 2008).

The majority of the models are developed for a specific country, being the spatial characterization and databases (of typology of buildings, energy infrastructure) less suitable for other countries, such as the Netherlands (Vreenegoor et al., 2008). Few studies assessed the potential of various heating technologies and demand-side efficiency improvements at national scale in the Netherlands (Heynen et al., 2017; Hoogervorst, 2017; Möller et al., 2019; Naber et al., 2016; Paardekooper et al., 2018). However, an appropriate evaluation of local heat resources and demands requires a higher level of geographical resolution (Möller et al., 2019). An assessment at the neighbourhood scale can take into account the relationships between buildings and the surrounding area (e.g. district morphology, microclimate, spatial restrictions and potential and viability of local heating sources). In this context, the assessment of various sustainable heating technologies in the Netherlands has been scaled down to regions and cities (van der Molen et al., 2018; van den Wijngaart et al., 2018; Maria Jebamalai et al., 2019; Wesselink et al., 2018; Ajah et al., 2007). Nevertheless, no studies are found looking at methods that assess different heat supply options and building shell improvements for different types of buildings at the neighbourhood level.

Earlier studies has pointed out the focus of the scientific community on models that have little use among local practitioners because of the model complexity and the low alignment of tools with the objectives and context of the local planning, where the decision-making for heat or energy planning takes place (Gibson et al., 2017; Bush & Bale, 2019; Ben

Amer et al., 2020). It seems, thus, necessary to introduce ‘locally applied’ methodologies to the scientific community and critically evaluate these.

Aim of the research

The aim of this work is twofold: (i) to contribute to the methodological development of available energy models that can compare alternative heating systems and energy-efficiency gains in existing buildings at the neighbourhood level and (ii) to assess a methodology that is being used by local governments to draw potential heat strategies.

For this purpose, this work uses the Vesta Multi Actor Impact Simulation model (*Vesta MAIS*). *Vesta MAIS* is the national methodology the Dutch central government has made available and is being applied by municipalities and local heat planners to formulate local strategies towards the decarbonization of heating systems in buildings. This open-source model (for a more detailed description, see the ‘Methods’ section) has already demonstrated to be a useful tool for assessing costs and emissions of potential low-carbon heating strategies for buildings at city level in medium and long-term analyses (van den Wijngaart et al., 2018; van der Molen et al., 2018). However, at the time of carrying out this research, the tool was not yet applied at neighbourhood level. As the model offers high adjustability in both operation and input data, it can indicate the potential applicability at the local level.

This paper is structured as follows. The method and the case study is first introduced, followed by the ‘Results’ section. The ‘Discussion’ section discusses the significance of the main findings and puts forward the limitations. Finally, the ‘Conclusions’ section ends with the concluding remarks.

Methods

The methods section first introduces the case study. Next, the general characteristics of the *Vesta MAIS* model are presented followed by key input data and the scenarios used to assess low-carbon heating systems in the study area. Finally, this section explains the parameters investigated in the sensitivity analysis.

The case area

The case study is carried out in the Dutch neighbourhood of Overvecht in the city of Utrecht, in which the local government is carrying out a pilot project to gain experience in the process of removing the natural gas supply in existing buildings.

Overvecht, encompassing an area of 8.48 km^2, has currently 34,293 inhabitants and consists of ten sub-neighbourhoods (Fig. 1). A total of 15,884 residential buildings and 1925 non-residential buildings are present (Utrecht Municipality, 2019).

Residential buildings are largely high-rise apartments built in the period 1965 to 1974 (Fig. 2), while buildings with a non-residential function are mainly

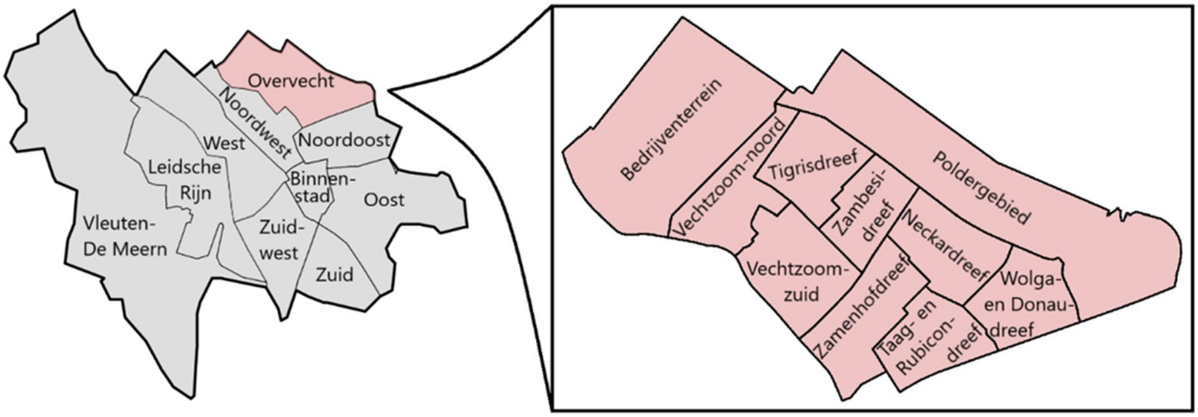


Fig. 1 Location of the neighbourhood of Overvecht in the city of Utrecht (left) and the sub-neighbourhoods of Overvecht (right)

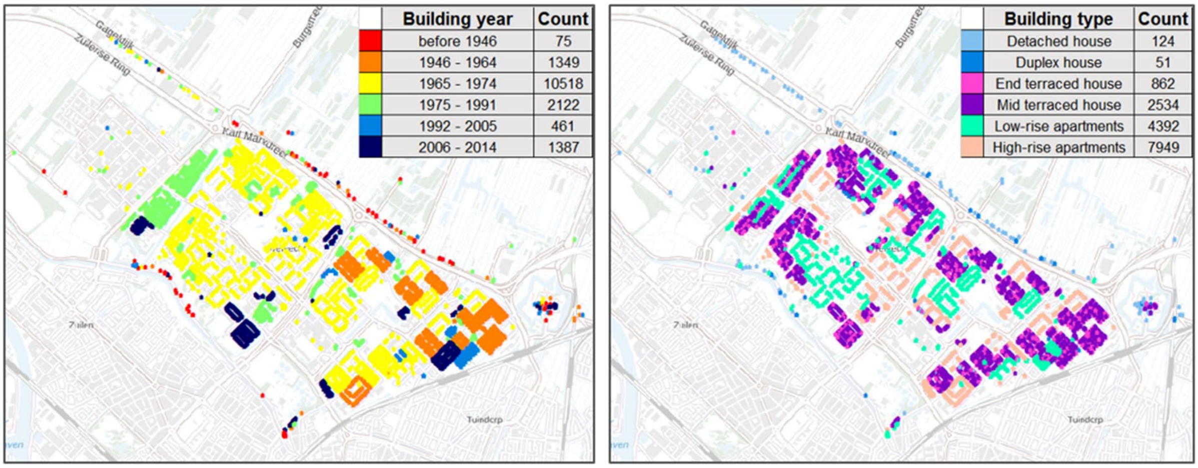


Fig. 2 Building construction year (left) and building types (right) of residences in 2019 in Overvecht (PDOK, 2019)

constructed in the period up to 1975 (Fig. 3). The majority of the buildings are poorly insulated (Fig. 4).

Figure 5 shows the current heat demand density in the neighbourhood. The final heat demand in Overvecht in 2019 was 707 TJ, from which 49% is supplied by individual natural gas boilers and 51% by a HTDH system (Fig. 6). The HTDH comprises two combined cycle gas turbines (CCGT) with an electricity and heat capacity of 328 $\mathrm{MW_e}$ and 290 $\mathrm{MW_{th}}$ respectively, and a supporting gas-fired auxiliary boiler of 25 $\mathrm{MW_{th}}$ (Eneco, 2014).

Vesta MAIS model

The *Vesta MAIS* model is a techno-economic spatial energy model developed by the Netherlands Environmental Assessment Agency (van den Wijngaart et al., 2017). The model is primarily designed to explore on yearly interval periods the technical and economic impacts of potential opportunities for reducing and replacing natural gas consumption in buildings. The model does not optimize the outcomes (i.e. it does not calculate what is the most cost-effective route to

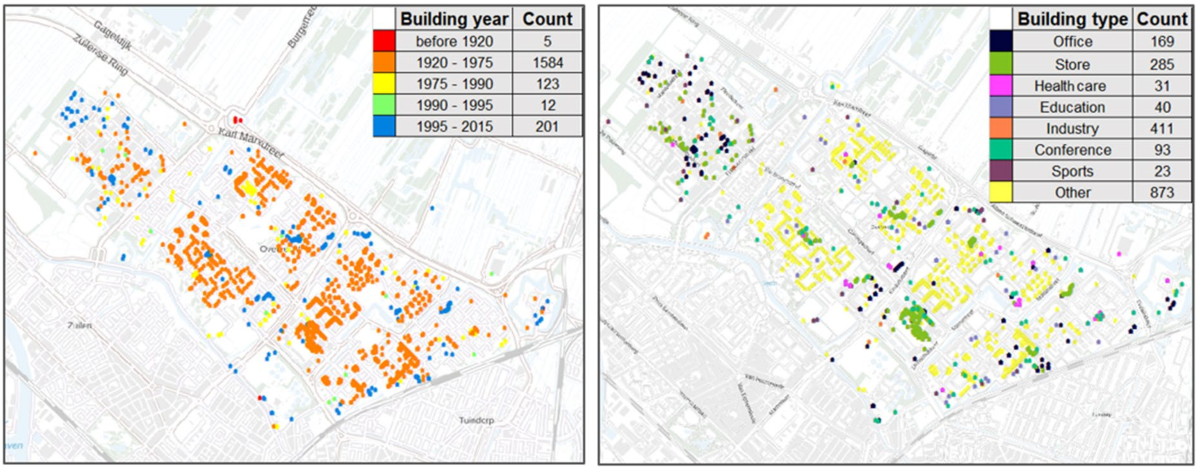
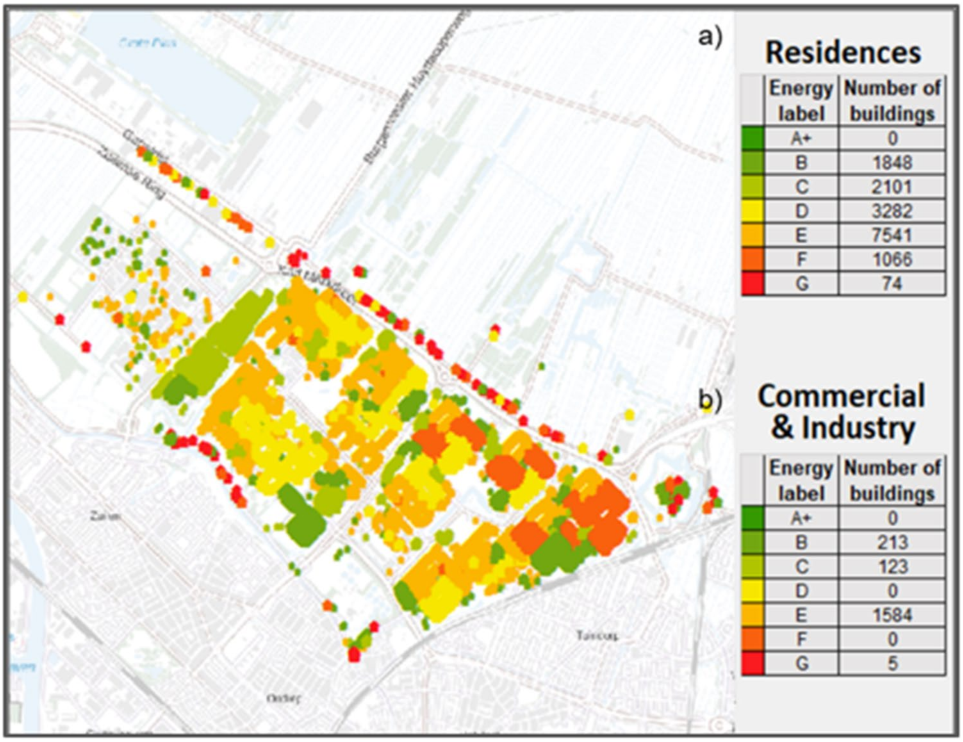


Fig. 3 Building construction year (left) and building types (right) of non-residential buildings in 2019 in Overvecht (PDOK, 2019). The category ‘Other’ contains buildings not defined in the above depicted categories (e.g. restaurants, libraries and car garages)



Residences

	Energy label	Number of buildings
🟩	A+	0
🟩	B	1848
🟩	C	2101
🟨	D	3282
🟧	E	7541
🟧	F	1066
🟥	G	74

Commercial & Industry

	Energy label	Number of buildings
🟩	A+	0
🟩	B	213
🟩	C	123
🟨	D	0
🟧	E	1584
🟧	F	0
🟥	G	5

Fig. 4 Energy labels of residential buildings (**a**) and non-residential buildings (**b**) (CBS, 2018; RVO, 2019b)

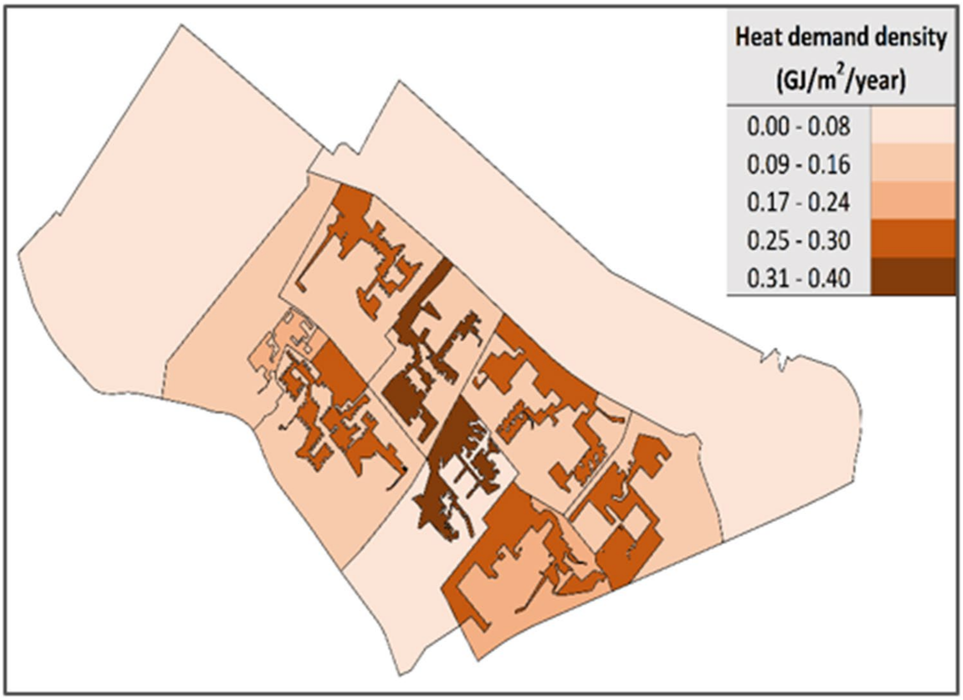


Fig. 5 Heat demand density (in GJ/m^2 of land) in 2019 extracted from the *Vesta MAIS* database

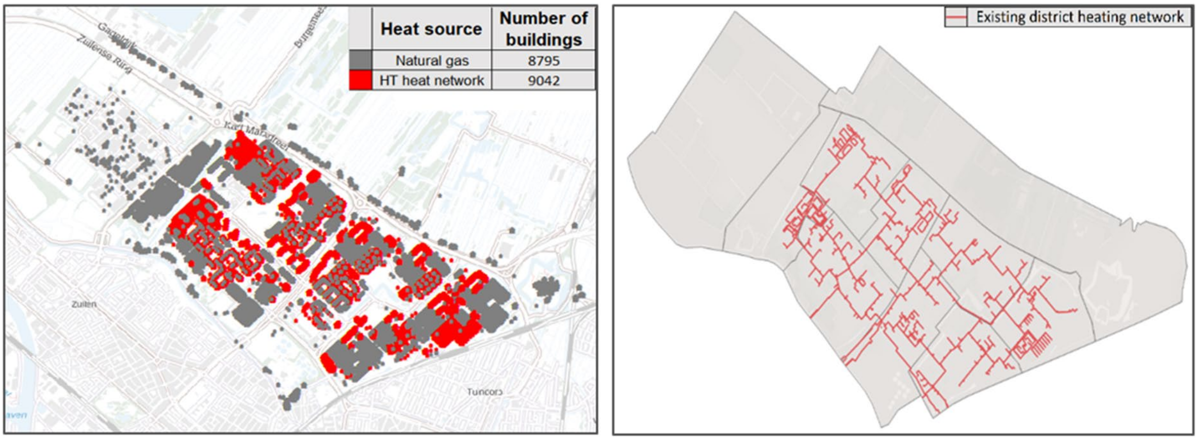


Fig. 6 The number of buildings supplied by existing heating technologies (left) and existing district heating network in Overvecht in 2019 extracted from the *Vesta MAIS* database

decarbonize buildings) or simulate the outcomes (i.e. it does not determine the most probable future). *Vesta MAIS*, which has demonstrated to be suitable for national and regional level (van den Wijngaart et al., 2018; van der Molen et al., 2018), takes into account local conditions such as spatial data at building level and data on local heat sources. Version 3.3 of the model was employed in this research.

Figure 7 provides an overview of the structure, modules and input data in *Vesta MAIS*. The first three modules represent the input data feeding the model. Building typology data is extracted from the national building spatial database (PDOK, 2019) and is modelled as a collection of archetypes buildings with a residential or non-residential function. Six types of residential buildings, eight types of non-residential buildings and six construction periods (Table A1 and Table A2, Supplementary material) are modelled by *Vesta MAIS* on an individual basis for the case area. The model adds different layers of spatial regions such as provinces, municipalities and sub-neighbourhoods defined by the National Statistics Office (CBS, 2018) allowing the user to aggregate areas up to the desired spatial level.

Building insulation data are extracted from the Dutch national database (RVO, 2019a) and range

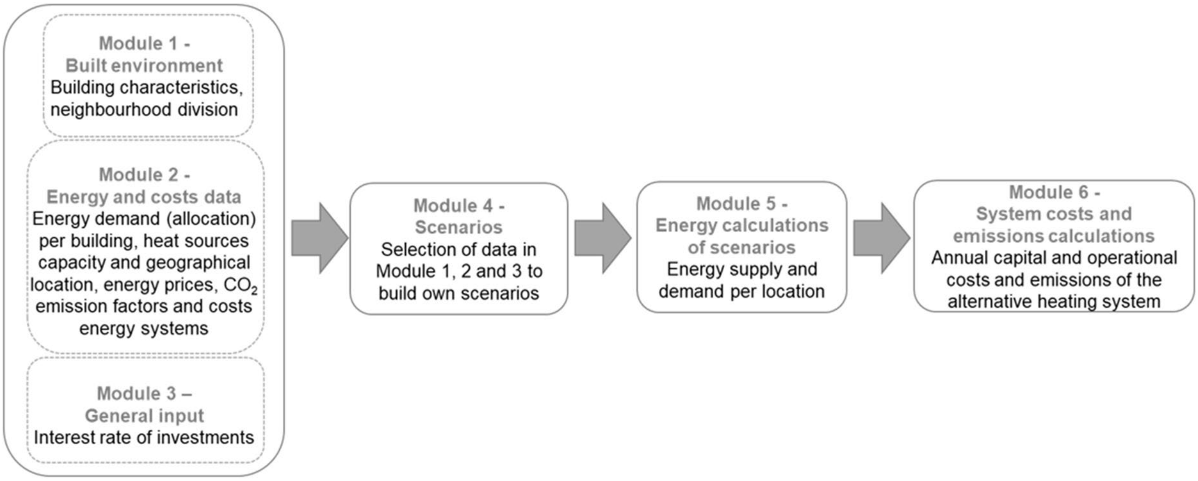


Fig. 7 Overview of the operational framework of the *Vesta MAIS* model

from energy label G (poorly insulated) to A+ (well-insulated) as depicted in Fig. 4 and Tables A1 and A2 (Supplementary material). Energy labels per building are determined from the energy label database using fuzzy string matching algorithms. This process initially matches the addresses based on house/apartment/building numbers at the individual building level. For buildings where energy label data is unavailable, an estimation is made based on average energy performance values for that type of dwelling (e.g. building type and construction period). The model assigns the final heat demand to each of the buildings based on the spatial data of each dwelling (i.e. year of construction, building type), floor space, energy label, heating system and climate conditions.

The model assigns the final heat demand to each of the buildings based on the spatial data of each dwelling (i.e. year of construction, building type), floor space, energy label, heating system and climate conditions. The model uses Dutch average climate data measured from 1995 to 2005 and accounts for annual temperature variations and future temperature rise due to climate warming on heat demand by applying a correction using degree days (Koninklijk Nederlands Meteorologisch Instituut, 2014; Schepers & Leguijt, 2017). Using the high ambition scenario of the Netherlands Environmental Assessment Agency (PBL, 2015), a temperature increase of 1 °C in average temperature in 2030 compared to the period 1980–2010 is assumed. This leads to a heat demand reduction of 10% in 2030 compared to 2019 levels.

Next, the electricity demand for electrical equipment is assigned per building type. *Vesta MAIS* assumes cooling for residences only to happen after implementation of aquifer thermal energy storage (hereafter ATES) and for non-residential buildings. The calculation of the heat demand for individual natural gas-fired boilers assumes in-building heat losses (5% for space heating and 10% for warm water). The heat and electricity demand and efficiency assumed for each building typology using individual natural gas-fired boilers are depicted in Tables A1 and A2 (Supplementary material).

The presence of a DH network in *Vesta MAIS* is determined by the share of buildings connected to the network, as registered by the National Statistics Office (CBS, 2018). The standard configuration of the model uses a significant simplification here. No connection to DH is assumed when less than 50% of the buildings are connected to DH (see, for instance, the sub-neighbourhood of ‘Vechtzoom-noord’; Fig. 8). The opposing assumption is made when more than 50% of all buildings are connected to DH. Under this simplification, seven of the ten sub-neighbourhoods of Overvecht (highlighted in red in Fig. 8, left) would be entirely supplied by HTDH, which is significantly deviating from the actual situation (Table A5, Supplementary material). A model adjustment using the geographic information system application QGIS (QGIS, 2019) has been implemented to circumvent this rule. The standard CBS neighbourhoods are represented by a shapefile, a polygon whose coordinates reflect the geographical location of the sub-neighbourhood boundaries. The polygons for areas where DH is present are split up into two separate polygons: a polygon which represents the part of the sub-neighbourhood which has DH and a polygon which

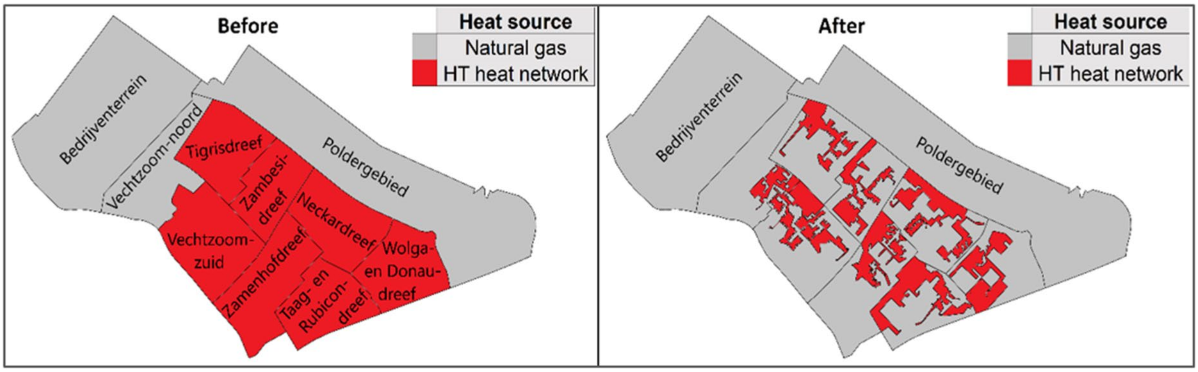


Fig. 8 Buildings assumed to be fed by HTDH in the standard configuration of the model (left) and after the adjustments made (right)

represents the area that does not or hardly have DH connections. Next, the share of DH connections in the CBS database is adjusted to account for the new polygons. After the adjustment, all the sub-neighbourhood of Overvecht affected by this problem were divided into two areas; one with HTDH and the other one without HTDH. This lead to a total of eighteen sub-neighbourhoods from the initial ten (Table A5, Supplementary material).

In order to ascertain whether *Vesta MAIS* is a reasonable representation of the energy and building system in the starting situation in Overvecht, various parameters have been validated with data from the PICO database (PICO, 2019). As shown in Table 1, the validation discloses a very small deviation in the number of buildings considered for the studied neighbourhood. This might be caused by the different building definitions and/or building use in both databases. The assumed electricity demand values are also comparable. The larger differences originate in the assumed higher natural gas demand (16% more in *Vesta MAIS* than in PICO) which may be explained by the fact that buildings are in reality better insulated than what *Vesta MAIS* assumes. Combined, the modelled electricity and natural gas use deviate 11% from the actual use.

Table 1 Validation of the reference input data in *Vesta MAIS* in 2018 for Overvecht with the PICO database (PICO, 2019)

Energy demand	PICO	Vesta MAIS	Deviation
Nr. buildings	18,203	17,809	− 2%
Electricity (GJ)	216,803	223,445	+ 3%
Natural gas (GJ)	299,718	348,727	+ 16%
Total (GJ)	516,521	572,172	+ 11%

Scenarios and key assumptions

The information from modules 1–3 of Fig. 7 is used to draw five decarbonization scenarios that either reduce or remove natural gas supply in buildings (see Table 2). The scenarios are compared with a reference scenario. For each scenario, the following parameters are calculated: (i) final energy demand; (ii) CO_2 emissions and emission reductions from reference; (iii) system costs (which reflect the costs from a societal perspective); (iv) system costs per home-equivalent, in which the term home-equivalent is used to convert the floor space of different types of building sizes into sizes of a stereotypically sized ‘home’. In this study, one home-equivalent is set to 130 m^2 floor space which is the average size of a Dutch home and (iv) the levelized costs of heat (LCOH). In order to outline potential low-carbon heating strategies in the neighbourhood, this research uses the lowest total system costs and the lowest emission reductions as criteria.

Depending on the scenario, the buildings are upgraded to energy label B ($Rc = 2.5\ m^2\ K/W$) or to label A+ ($5.0\ m^2\ K/W$). The theoretical energy savings from building insulation are based on an earlier analysis performed for thirteen building types (Agentschap, 2011). The theoretical consumption is subsequently adjusted to the actual energy consumption measured for representative residences of the Netherlands (Ministry of the Interior and Kingdom Relations and CBS, 2011). The final energy demand per building type resulting from building refurbishments and the associated investments are depicted in Tables A3 and A4 (Supplementary material). The present research considers the average of minimal and maximal investment costs of the values presented in Tables A3 and A4.

The base load and peak load capacity of the DH network considered (Table A6, Supplementary material) influences the investments for infrastructure and determines whether available heat sources are sufficient to supply heat to an area. *Vesta MAIS* assumes that the system is continuously running at base load capacity and provides 80% of the yearly heat demand volume. Natural gas back up boilers are used during peak loads and provide 20% of the yearly heat demand. The assumed ratios are based on averages from typical DH networks that currently exist in the Netherlands (Schepers & Leguijt, 2017).

The future development plans by the existing local DH supplier to gradually substitute the heat from the CCGT with more sustainable heating sources are summarized in Table 3. A recently constructed biomass plant will shortly deliver heat from wood waste to Overvecht (Eneco, 2018a). Additionally, there are also plans to extract heat from two large geothermal sources by 2025 and 2030, and a sewage treatment process by 2021, as well as from industrial waste heat (Eneco, 2018b). The gradual change towards renewable heat supply sources is included in the calculation of the emission factors of all scenarios as shown in Table 4.

Table 2 Description and assumptions in the modelled scenarios

Scenario [abbreviation]	General assumptions[a]	Heating system	Buildings refurbishment
1. Reference [Ref]	Status quo. Gas grid partly renovated due to ageing	Individual natural gas boiler and heat from existing HTDH	None
2. Insulation to energy label A+ [Ins A]	Same assumptions as in reference	Individual natural gas boiler and heat supply from existing HTDH	Refurbishments up to label A+ for all buildings (R value 5 m^2 K/W)
3. Insulation to energy label B [Ins B]	Same assumptions as in reference	Individual natural gas boiler and heat supply from existing HTDH	Refurbishments up to label B for all buildings (R value 2.5 m^2 K/W)
4. Heat pumps and HTDH [HP_HTDH]	Implementation of individual air-source HPs. Reinforcements in the electricity grid	Large-scale implementation of heat pumps and heat supply from existing HTDH	Buildings connected to the existing HTDH maintain current insulation levels. All the other buildings are insulated to label A+ (R value 5 m^2 K/W)
5. HT heat network [HTDH]	Existing HT heat network is expanded to all sub-neighbourhoods. Temperature of sources up to 90 °C or up to 70–80 °C with central upgrading. No reinforcements in electricity grid	Expansion of the existing HTDH	None
6. Aquifer thermal energy storage and HTDH [ATES_HTDH]	Underground double-source ATES at max 15–20 °C with central upgrading via a ground-sourced HP. Buildings are equipped with LT supply systems. Reinforcements in the electricity grid required	LT heat network based on ATES and heat from existing HTDH	Buildings connected to the existing HTDH maintain current insulation levels. All the other buildings are insulated to label A+ (R value 5 m^2 K/W)

[a] Note that *Vesta MAIS* does not allow the implementation of other heating technologies when there is already an alternative system (e.g. DH) other than individual natural gas-fired boilers. This means that 8 of the 18 sub-neighbourhoods being currently fed by HTDH (Fig. 8), which are 49% of total buildings, maintain this system in all the studied scenarios

The assumptions under the high ambition scenario of the Netherlands Environmental Assessment Agency (PBL, 2015), which is in line with stringent global mitigation scenarios, are used in the model to calculate the future developments of emission factors and commodity prices of the various energy sources (Table 4).

Table 3 Fuel mix supply in the current HTDH network and the planned developments by the local heat supplier until 2030 (Eneco, 2018b)

	Share of heat supply			
	2019	2020	2025	2030
CCGT	80%	50%	20%	0%
Natural gas auxiliary boiler	20%	10%	10%	10%
Biomass	0%	40%	40%	30%
Sewage treatment	0%	0%	10%	10%
Geothermal	0%	0%	20%	40%
Industrial waste heat	0%	0%	0%	10%

In the ATES heating system, storage and recovery of thermal energy are achieved by extracting and injecting groundwater from groundwater wells. *Vesta MAIS* includes a map with water restriction areas where the implementation of ATES is not allowed in the shallow ground (e.g. in drinking water extraction areas). In the present analysis, a water restriction area is located in the sub-neighbourhood of ‘Poldergebied’, which means that the implementation of ATES is not possible in that area.

System costs comprise of capital expenditures (CAPEX) and operational expenditures (OPEX). Depending on the scenario, CAPEX encompasses the investments for buildings refurbishments, implementation of HPs, of ATES system, the expansion

Table 4 Emission factors and commodity prices in the starting situation and in 2030 (PBL, 2015; Schepers & Leguijt, 2017; Matthijsen, Aalbers, and van den Wijngaart 2016)

		2019	2030	% change 2019–2030
Emission factor	Natural gas (kg CO_2/GJ)	50.6	50.6	0
	Electricity (kg CO_2/ MWh)	454.0	60.8	– 86.6
	ATES heat (kg CO_2/GJ_{th})	–	7.4[a]	N/A
	HT heat, including auxiliary boiler (kg CO_2/GJ_{th})	28.8	10.8	– 37.2
Heat cost	(€/GJ_{th})	7.2	6.4	– 10.6
Electricity cost	(€/MWh)	6.1	8.3	36.1
Natural gas cost	(€/GJ)	5.9	3.8	– 35.0

[a] Emissions from ATES come from the electricity of the central HP, and consider the HP efficiency, and the recovered heat by cooling in the summer

of the HTDH network, for removing the natural gas grid, for reinforcing the electricity grid and for renovating the existing natural gas grid in those scenarios that maintain this system (see Table 2). These are spread over the technical lifetime of each technology using an annualized calculation with a social discount rate (r) of 4% (Schepers & Leguijt, 2017). Taxes, subsidies and cash flows between actors (e.g. what a consumer pays to a heat supplier) are excluded from the system costs.

This study assumes that all heating options are operational in 2030 to meet households' heat demand, but with different projected future lifetimes and investment costs. Detailed techno-economic data for each scenario is summarized in Table A6 (Supplementary material). For a more detailed description of the data, formula's and assumptions in *Vesta MAIS*, see the model documentation (Schepers & Leguijt, 2017; van den Wijngaart et al., 2017).

The calculation of the LCOH for the implementation of the different heating technologies follows Eq. 1:

$$LCOH = \frac{\sum \left[\frac{CAPEX_t + OPEX_t}{(1+r)^t}\right]}{\sum \left[\frac{E_t}{(1+r)^t}\right]} \qquad (1)$$

where CAPEX are the capital expenditures in year t; OPEX are the O&M expenditures and fuel costs in year t; $(1 + r)^t$ is the discount factor in the year t, with the social discount rate (r). E_t is the heat produced in the year t.

The investment costs of the technologies evolve following technological learning. The development of productivity levels and future material and labour costs are assumed to follow an 'optimistic' and a 'pessimistic' pathway. The reduction in costs due to technological learning is higher under optimistic assumptions than under pessimistic conditions. The assumed developments of various costs components associated with the heating systems and with the improvements at the building shell are shown in Fig. 9. *Vesta MAIS* assumes that different components of the DH network follow a different reduction curve. By default, the model considers the average between these maximum and minimum values. The increasing trend of the pessimistic pathway for costs of building refurbishment is explained by the expected rise in costs for skilled labour and material, and limited technological learning. This development is in line with earlier published work where insulation costs are expected to rise with 0.5–1% per year (Economisch Instituut voor de Bouw, 2019).

Sensitivity analysis

To determine the robustness of the results, a deterministic sensitivity analysis has been performed to assess how model results are sensitive to parameter values. Three parameters, which have been identified in earlier research to be highly uncertain or significantly influence the model outcomes of the decarbonization scenarios (Hoogervorst et al., 2019), are assessed: (i) the commodity price of electricity; (ii) the investment costs of building refurbishments, and (iii) the development of investment costs of heating systems due to technological learning. Additionally, two other parameters are also included in the sensitivity analysis: (i) the reduction of the carbon intensity of electricity production to account for less ambitious but plausible

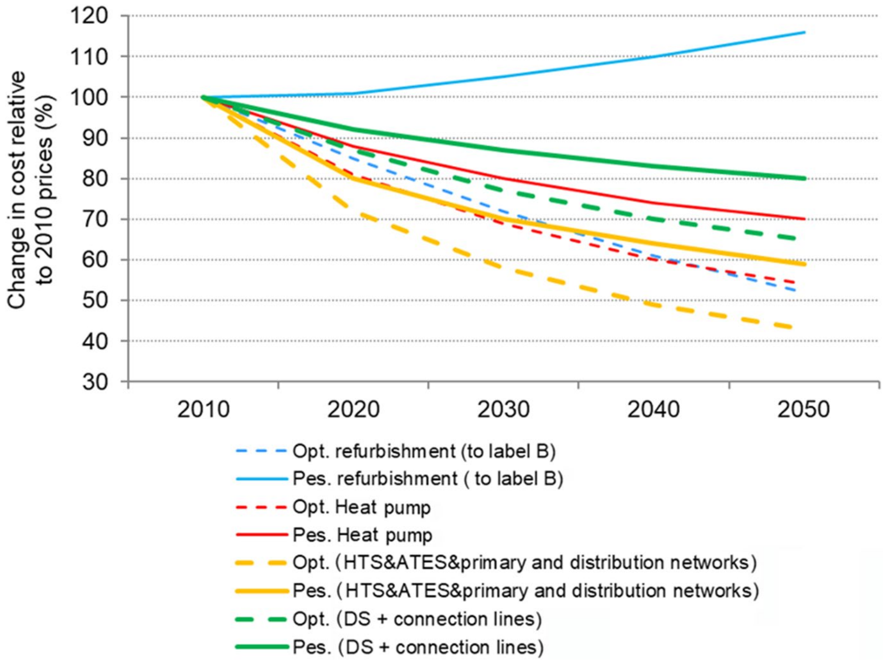


Fig. 9 Future costs development as included in *Vesta MAIS* for various technologies. Opt = optimistic pathway of cost development, Pes = pessimistic pathway of cost development. Data based on Schepers and Leguijt (2017) and CE Delft (2014)

developments and (ii) the investment costs of ATES systems as the investment costs of this heating system can have strong variability (Schüppler et al., 2019). The gas price, which will negatively affect the economic performance of the reference scenario, is excluded because the present study focuses on parameters that influence the decarbonization scenarios.

The five studied parameters and the studied range are summarized in Table 5. The upper and lower bounds were established based on literature and/or the value range of certain input data in *Vesta MAIS* as follows. The social discount rate considers typically used values in public projects with various perceived risks (Armitage, 2017). Recent projections are used to establish the range of the electricity price in 2030 and the future reduction in electricity-related emissions (PBL, 2019). As depicted in Table 5, the investment costs of building refurbishments and the effect of various technological learning development on the default investment costs are varied between the minimum and maximum values of the model input data.

Next, our research studies the impact of different discount rates. Although the social discount rate is typically fixed for a specific country and is therefore not subject to uncertainty, unlike other parameters

Table 5 Parameters and values range assessed in the sensitivity analysis

Parameter	Default value	Range	Units
Electricity commodity price in 2030	0.083	0.040–0.095	€/kWh
Investment costs building insulation	Average value of max and min values from Tables A3 and A4 (Supplementary material)	7–164 depending on building type, see Tables A3 and A4 (Supplementary material)	€/m^2
Effect of technological learning in investment costs	Average of the minimum and maximum values of Fig. 9	Minimum and maximum values of Fig. 9	%
Reduction in electricity-related emissions by 2030 compared to 2019 values	87	30–50	%
Investment costs of ATES systems	725	± 50% from default value	€/kW

such as investment costs and energy prices, it is useful to show the impact on the results of a varying discount rate. Based on Armitage (2017), the social discount rate is varied from 3 to 6% which are typically used rates of public projects with various perceived risks.

Results

This section presents the model outcomes regarding the final energy demand, emissions, the annualized system costs and LCOH for the studied scenarios in Overvecht. Based on these results, several heating strategies are identified for the neighbourhood. Lastly, the results of the sensitivity analysis are discussed.

Final energy demand and emissions

Figure 10 presents the calculated energy demand in 2030 and how energy efficient the studied scenarios are with respect to each other. The total final energy demand is reduced compared to the reference in all projected scenarios, except when the existing HTDH is expanded. The low exergy content of the hot water used in HTDH, compared to using natural gas in the reference case, explains the higher heat demand. As 8 out of the 18 sub-neighbourhoods are assumed to maintain the existing HTDH, the demand for HT-heat is present in all scenarios.

The minimized heat distribution losses when LT heat supply is provided, combined with higher refurbishment levels and better system efficiency, reduce the heat demand significantly, as it is observed in the results of Fig. 10 of ATES and HP scenarios compared to that of HTDH. The largest heat demand reductions (42%) occur when individual HPs are installed (due to the large efficiency gain) and when the building shell of the building is upgraded up to the highest insulation label (41%). The results depicted in Fig. 10 also show that refurbishments up to label A+ bring nearly twice as much heat savings than when label B is attained. The reader should note that if all the buildings in the HP_HTDH scenario would be upgraded to label A+, as it is assumed in the Ins A scenario, the energy savings will be even higher.

Implementing HP at individual level leads to 33 TJ additional electricity against the reference (Fig. 10). Similar electricity consumption is obtained when a central HP in installed in the ATES scenario.

Figure 11 shows the contribution to total emissions in 2019 (29.1 ktCO$_2$) for DH (35%), natural gas (61%) and a minor share (4%) of emissions from the electrically powered pump, to carry the

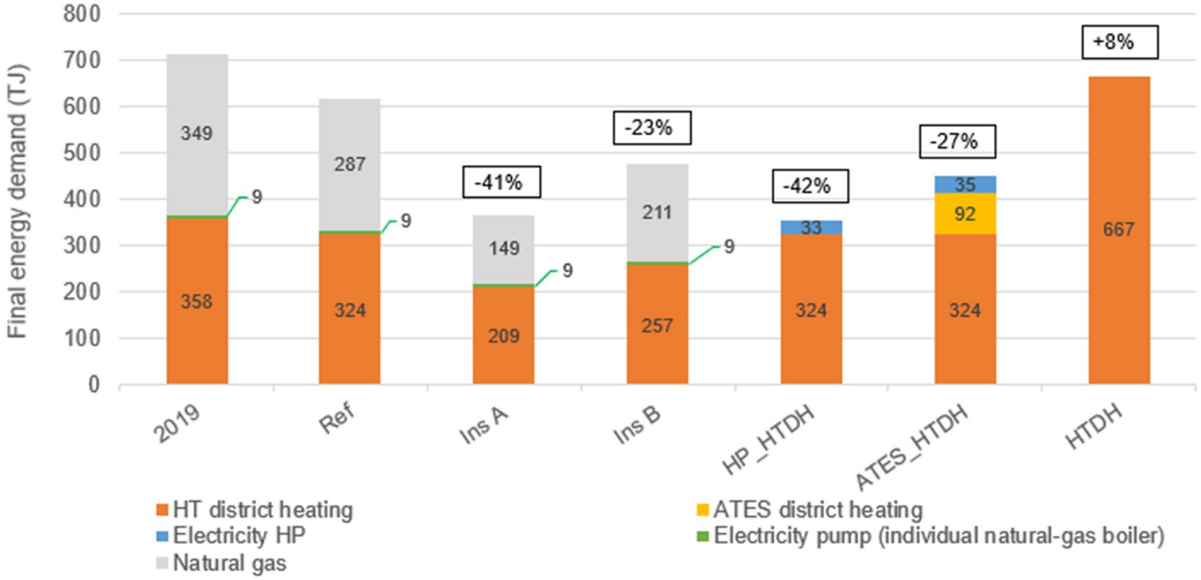


Fig. 10 Final energy demand and share per energy source in the starting situation (2019) and per scenario in Overvecht in 2030. In boxes, the percentual change in the low-carbon scenarios compared to reference

heat from the individual gas-fired boilers into the radiators. The rapid decarbonization assumed for the electricity sector in all the scenarios significantly decreases electricity-related emissions from current levels by 2030. This effect, in combination with higher energy-efficiency gains and the presence of building's refurbishments, causes LT electricity-based heating systems, such as HP or ATES, to reduce emissions by 75–80% compared to reference (right axis of Fig. 11). The planned decarbonization of the existing DH network in Overvecht can reduce emissions significantly (60% against reference). However, the differences shown in total emissions between the three studied alternative heating technologies is relatively small, especially among the HP and ATES scenarios. The results also indicate that the refurbishment of buildings in combination with a sustainable heating system is more effective in lowering emissions than the stand-alone measure.

Although the studied scenarios show a high potential for carbon mitigation, it is clear from Fig. 11 that fully carbon neutrality can only be achieved when the alternative heating source, either of the DH network or of the electricity, will not rely on fossil fuels. A complete decarbonization will bring additional costs to the scenarios.

Economic impacts

The required investments of sustainable energy measures bring additional costs to the system as shown in Fig. 12. The average additional annualized system costs per home-equivalent compared to the reference vary between 86 and 414€ (Table 6). The highest annual system costs are observed for the HP scenario, followed by the ATES scenario. The extra investment costs for the HP, the re-insulation of the building shell and the needed adjustments of the heating supply system in the building (e.g. radiators) make this technology more expensive compared to the reference. The additional yearly electricity costs in this scenario due to the implementation of the HP (0.8 M€) are compensated by the avoided natural gas consumption (2.5 M€).

The necessary building refurbishments in the HP and ATES scenarios cost nearly 5 M€, which represent 22 to 24% of the total costs and approximately the half of the costs when all buildings in the area are refurbished (Ins A and Ins B scenarios). While the costs associated with buildings refurbishments observed in the Ins A scenario are 45% more expensive than those of the Ins B scenario, it brings less than one third of the benefits in reducing energy demand and emissions (Figs. 10 and 11), and thus,

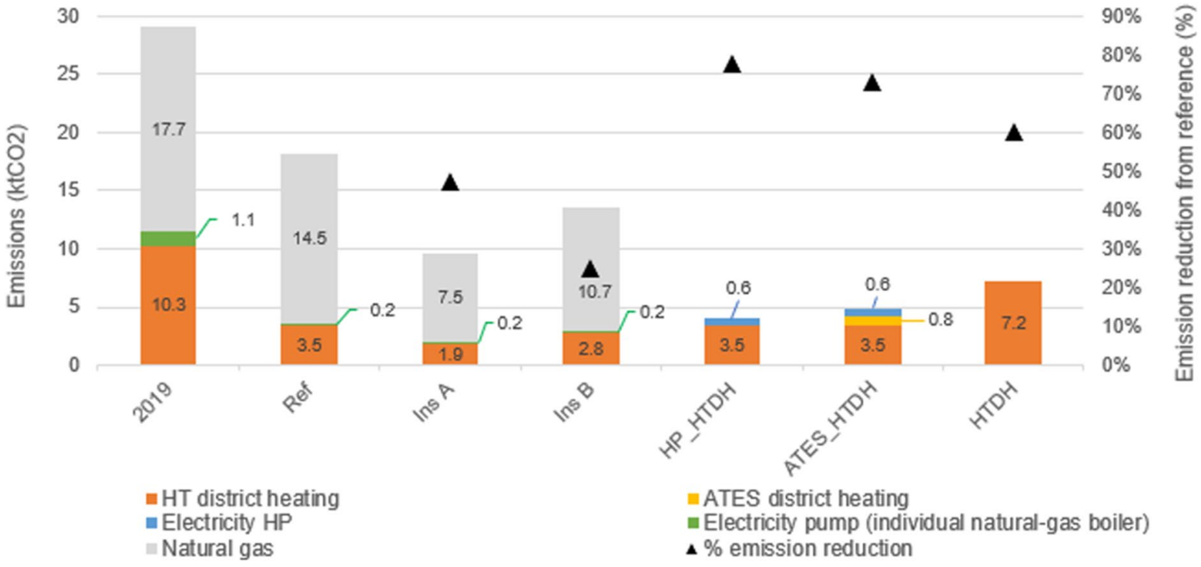


Fig. 11 Emissions per energy source (left axis) and emissions savings compared to the reference (right axis) per scenario in Overvecht in 2030

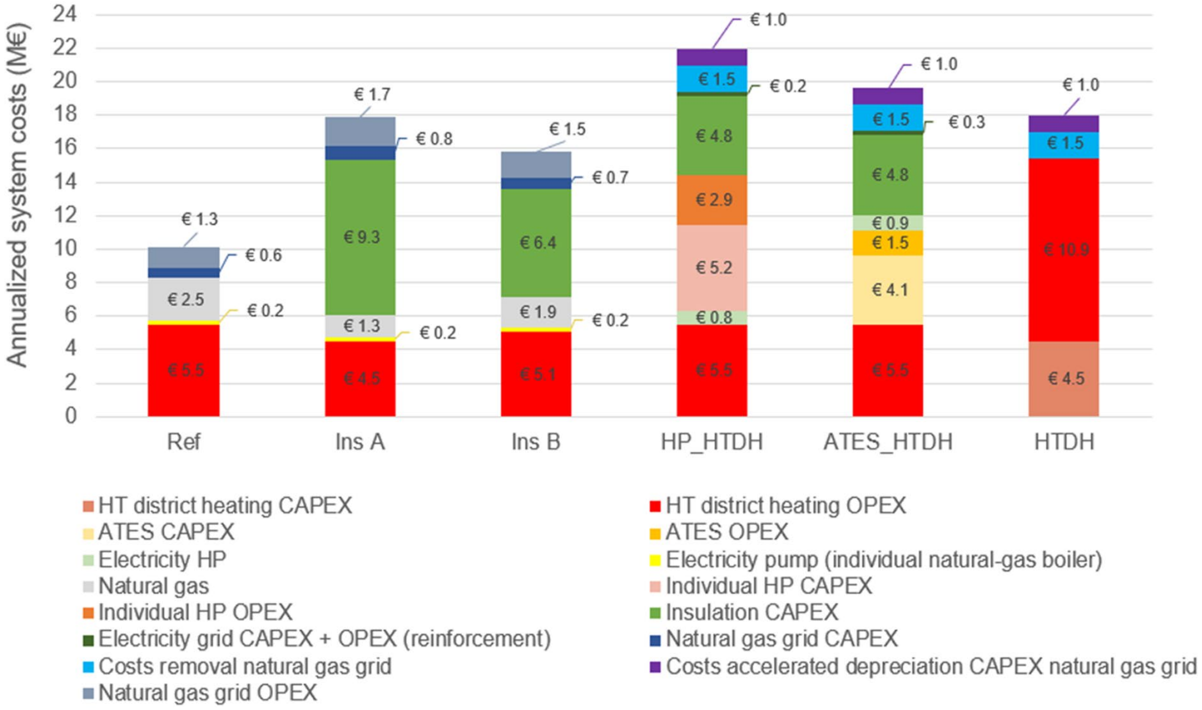


Fig. 12 Annualized disaggregated system costs per scenario in Overvecht in 2030

Table 6 Average of the additional annualized system costs per home-equivalent of the studied sustainable heating systems compared to the reference in Overvecht in 2030.

Heating system	Building insulation level	Average of the additional annualized system costs per home-equivalent compared to reference (€)[a]
Individual natural gas boiler	R value 5 m^2 K/W	121
Individual natural gas boiler	R value 2.5 m^2 K/W	86
Individual HP	R value 5 m^2 K/W	414
ATES system and central HP	R value 5 m^2 K/W	322
HTDH	Status quo (energy labels as in Fig. 4)	279

[a] The buildings that are connected to the existing HTDH network are not included in this calculation as *Vesta MAIS* considers no changes in these buildings

label B is more cost-efficient in reducing emissions than label A+. Important fuel costs savings are achieved compared to the reference, with 2.2 M€/year (label A+) and 1.1 M€/year (label B). Although the fuel costs savings does not compensate the higher costs associated due to building refurbishment (9.3 M€ for label A+ and 6.4 M€ for label B), the costs per home-equivalent are approximately 50% less than when this measure is taken in combination with the implementation of an alternative heating system (see second, fourth and fifth rows of Table 6). The costs from the removal of the natural gas grid represent 7–9% of the total annualized system depending on the scenario. When the natural gas grid is eliminated, there are still 5% of the total costs that need to be paid as the grid has not reached the end of its economic lifetime.

Expanding the existing HTDH infrastructure requires 4.5 M€ annualized costs (right bar, Fig. 12). The total system cost between HTDH and ATES networks only differ 11%. Although ATES systems usually show lower LCOH than HTDT networks as depicted in Table 7, the similar results observed in our analysis are explained by the lower operation costs of LT heating (70% fuel costs reduction from reference) and the extensive experience in the Netherlands with ATES systems where more than 85% of ATES world applications are operating in the country (Fleuchaus et al., 2018).

The LCOH of the analysed heating technologies and of the scenarios are compared to each other. As depicted in Table 7 two LCOH values can be calculated according to the system boundaries: (i) the heating system only and (ii) the heating system and the package of measures in each scenario (e.g. buildings insulation, removal of natural gas grid and reinforcement of electricity grid). The highest LCOH is observed by the implementation of HPs, followed by the ATES system. The LCOH of the current HTDH (based on CCGT) is similar to that of the individual natural gas boiler in 2019. In the projections for 2030 when the heat source changes to alternative HT heat sources (e.g. to geothermal and waste incineration), to LT heat (i.e. ATES) or to HP, the LCOH increases compared to the initial situation.

Our results for the HTDH and the starting situation with individual natural gas boilers are in line with earlier research (Table 7). The higher values found in the LCOH of the study of Gudmundsson et al. (2013) for natural gas-fired boilers can be explained by the different O&M costs and lifetime assumed for this technology. The LCOH results of ATES seem also to be aligned with the only study found (Yang et al., 2021), and the capital costs assumed in our modelling (725 €/kW) are in agreement with published literature of ATES systems installed in several North European countries, which ranged between 420 and 700 €/kW (Schüppler et al., 2019). The larger deviations in the LCOH results appear for the HP system compared to previous research. This can be caused by the different lifetime assumed for the HP in the other studies (20 years instead of 15 years). A 33% difference in the lifetime can impact considerably the annualized costs of technologies (Kesicki & Ekins, 2012).

Identification of a low-carbon heating vision for 2030 in Overvecht

Figure 13 (left) shows that the expansion of the current HTDH seems the most economically attractive and logical option in most parts of Overvecht. These are residential and business areas with medium heat demand density and medium-insulated buildings

Table 7 Levelized cost of heat for the various heating technologies in the starting year and in the modelled scenarios compared to earlier studies

	Current study		LCOH (€/kWh)					
			Other studies					
	Starting situation (2019)	Projected scenario (2030)	(Connolly et al., 2015)	(Colmenar-Santos et al., 2016)	(Gudmundsson et al., 2013	(Hansen, 2019)	(Wang, 2018)	(Yang et al., 2021)
Natural gas boiler	0.058	–	0.068	0.075	0.115–0.180	0.053	0.080	–
HTDH	0.054	0.067	0.059	–	0.066	0.041	–	–
HTDH (all costs)[a]	–	0.078	–	–	–	–	–	–
HP	–	0.246	0.075	–	0.161–0.216	0.076	0.110	–
HP (all costs)[a]	–	0.456	–	–	–	–	–	–
ATES	–	0.160	–	–	–	–	–	0.050–0.263
ATES (all costs)[a]	–	0.402	–	–	–	–	–	–

[a] ‘All costs’ refers to the costs associated with the package of measures in each scenario, next to costs of the implementation of the heating system only

(energy labels C to E). The exception are three sub-neighbourhoods which have high demand density and poorly insulated buildings (red areas in left map of Fig. 4). Two of them (orange areas in left map of Fig. 13) can be best connected to the ATES system ('Zambesidreef' and 'Wolga-en Donaudreef'). This result reveals that is economically more interesting to reduce heating demand by refurbishing the buildings up to label A and profit from the energy savings from a high efficient system in the 10-year studied period, than to not insulate the building and connect to a less energy-efficient HTDH network. The third sub-neighbourhood located in the polder area ('Poldergebied', blue area in left map of Fig. 13) is most suitable for individual HPs. The low heat density of this area (Fig. 5) with many detached and duplex houses, and the impossibility to implement ATES due to water restriction zones, makes HPs the most suitable technology.

A second economically plausible pathway is shown in the right map of Fig. 13, where the total annualized system costs differ 4% or less compared to the first identified option. Here, we see that the ATES system compete closely with the expansion of the HT heat network in more neighbourhoods. Although HTDH would not seem a logical choice at first in an area with low heat density, as the 'Poldergebied', the proximity of the buildings to the current existing DH infrastructure (Fig. 6, right) makes the expansion of the existing HTDH network also a conceivable system for this area. From these results, it can be generalized that DH, either HT or LT systems, combined with different levels of building refurbishments are comparable in terms of total costs in Overvecht.

Moving from a purely economic minimization to a CO_2 reduction perspective, a very different pathway for Overvecht is drawn, and the implementation of individual HP will clearly prevail as the best strategy (Fig. 14, left) followed closely ($\leq 4\%$ emission reduction difference) by the implementation of ATES with a central HP in most areas (Fig. 14, right).

Sensitivity analysis

The results of the sensitivity analysis impact the ranking of the economic attractiveness of the potential heating systems shown in Fig. 13 (left) in the following manner:

- The higher the discount rate, the more interesting is the implementation of HTDH, while a low discount rate (3%) benefits the implementation of the ATES system in most of the studied area.
- The effect of a more ambitious cost reduction due to technological learning than the one assumed as default favours the implementation of ATES systems over HTDH.
- Varying the electricity price does not affect the selection of the least costly heating strategy in any of the sub-neighbourhoods.

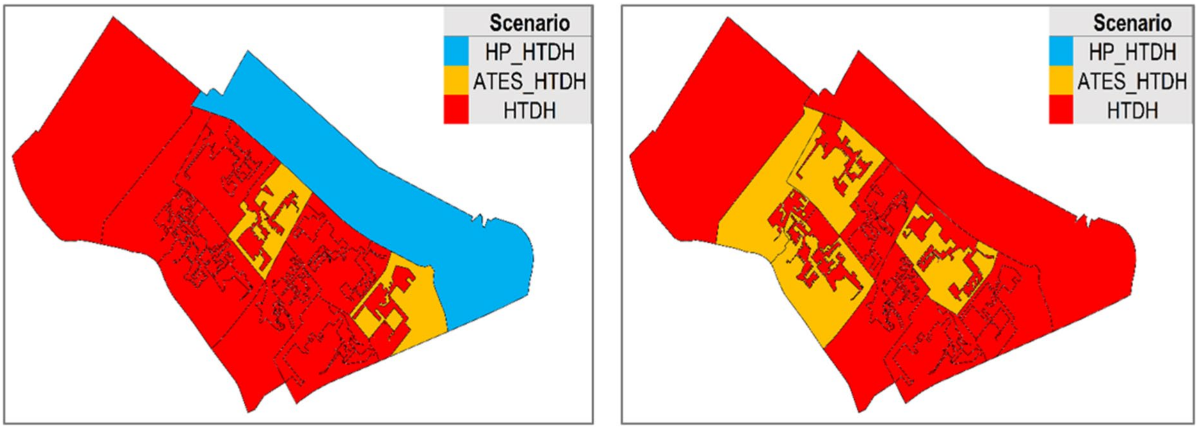


Fig. 13 Identified heating pathways with the lowest system costs (left) and the second lowest system costs (right) in Overvecht by 2030

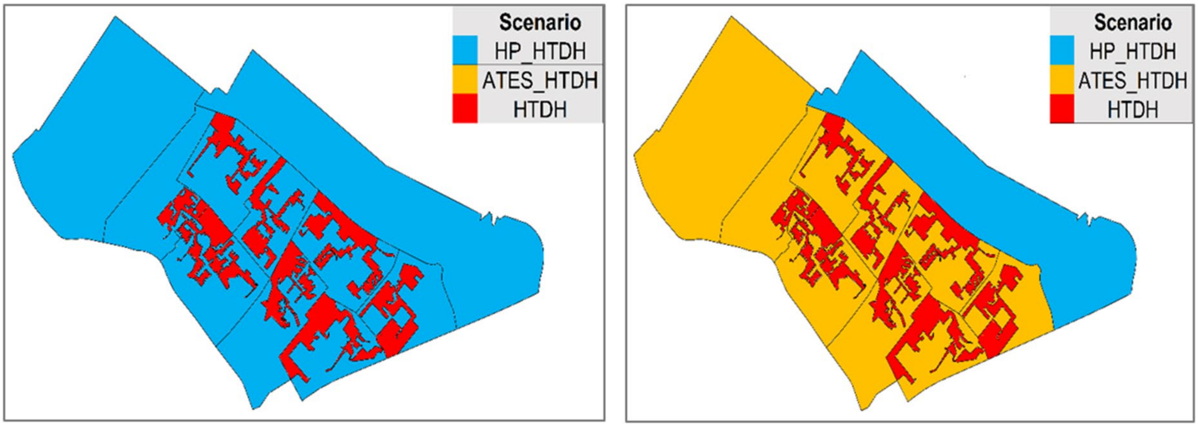


Fig. 14 Identified heating pathways with the lowest CO_2 reduction compared to reference in Overvecht by 2030

- A 50% increase of ATES capital costs will cause the two sub-neighbourhoods in Fig. 13 where ATES appear as the least costly option to switch to HTDH. However, if the ATES costs decrease by 50%, two sub-neighbourhoods ('Vechtzoom-zuid' and 'Tigrisdreef') will change from HTDH to ATES networks. In these four areas, thus, the choice for one or the other heating system—HT or ATES network—seems to depend largely on the costs of the ATES system.
- When conservative cost reductions in the refurbishment of buildings are assumed, ATES systems become more cost-competitive than the HTDH scenario in half of Overvecht's sub-neighbourhoods.
- An uniform trend observed in the sensitivity analysis for the majority of the studied parameters is that the economic attractiveness of ATES systems has shown to be very robust in the sub-neighbourhood of 'Wolga-en Donaudreef'. This is an area with poorly insulated buildings with high demand density.
- The sensitivity analysis also demonstrate robust results for five sub-neighbourhoods with medium heat demand density, and medium-insulated buildings ('Taag-en Rubicondreef', 'Zamenhofdreef', 'Neckardreef', 'Bedrijventerrein' and 'Vechtzoom-noord'), where the existing HTDH network appears as the most logical strategy.
- Likewise, high robustness is shown in the 'Poldergebied', an area with very low heat demand density and many stand-alone buildings, where the implementation of decentralized heating with individual HPs is maintained.

The ranking of the heating alternatives depicted in Fig. 14 (left) according to the CO_2 reduction is not affected when a lower decarbonization rate of electricity-related emissions takes place than the one assumed in the present study. A higher emission factor in the electricity sector will impact the CO_2 reduction effectiveness more of individual electricity-based technologies (i.e. HP) than the implementation of central heating systems based on electricity such as ATES systems.

Discussion

This section starts with a brief discussion on the applied approach and on the key results and ends by identifying limitations and recommendations for further research.

Reflection on the Vesta MAIS application at neighbourhood level and results

An approach for the planning and decision-making of potential low-carbon pathways for buildings at the neighbourhood level is proposed. The *Vesta MAIS* environment and approach presented in this research can be used as an example for developing models at neighbourhood scale in other countries. The application of the method should always be complemented with the same level of detail as used in *Vesta MAIS* (e.g. buildings characteristics, potential heating sources) to be able to carry out an assessment at this spatial level.

The *Vesta MAIS* model is applied in this research and one main shortcoming of the method is identified and addressed. The standard modelling approach embodied in the model is improved by accurately representing existing HTDH networks in a neighbourhood. This is an important novelty of the model development and its application at a low geographical scale, which leads to more reliable results in areas where HTDH networks provide heat only to some buildings. This adjustment, which has been later incorporated in the newest version of the model, highlights the importance of including more accurate local data in the modelling, which is not uniformly available at higher spatial levels.

Although the model selects by default the heating technology based on the lowest system costs, this study circumvents this rule by forcing the model to simulate the implementation of various heating systems based on two criteria: the lowest system costs and the highest emission reduction. The fact that other criteria rather than purely cost minimization is used in the selection of the local strategy can add value on the future application of the model, especially for local governments with higher sustainability ambitions.

The results of our research show that the potential of HT or LTDH, combined with building refurbishments, is high for the studied neighbourhood. To understand the impact of the synergies between the optimal network temperature and levels of insulation further research is required. Individual HP are most feasible for areas with low heat demand density. From the point of view of local decision-makers in the choice between HT and LTDH networks, next to the efficiency gains, there are additional benefits associated with LT systems that are key from a the strategic point of view (e.g. higher ability to incorporate renewables, storage and cooling options). Cascading the temperature of existing HTDH towards LT levels is, thus, the future of DH networks. The mentioned advantages are important as there is an increasing need for achieving greater energy savings, for peak shaving and for cooling demand globally. Furthermore, as LT heat networks are suitable for small scale, these systems are gaining significant attention. This is particularly relevant in the Dutch context, with a growing amount of local initiatives that aim to produce their own heat at community level. Several international projects on converting old HTDH towards LTDH in existing buildings can serve as successful examples for the Dutch heat transition (IEA, 2017; Rutz et al., 2019).

Reducing heat demand in existing buildings combined with the implementation of sustainable heating systems is the most cost-efficient in reducing emissions that as a stand-alone measure. However, when looking at the total system costs per home-equivalent investing in energy efficiency as a first step towards a low-carbon heating system can be seen as a non-regret transition step by local governments. These are easier to realize than changing the entire heat supply and the related infrastructure and can bring progressively both more consciousness and comfort among the final consumers before the whole heat supply is changed. In this context, numerous Dutch municipalities are setting up large renovation programs to shift gradually towards a fully decarbonized low-temperature heating supply system.

Limitations and opportunities for further application

Several limitations of this research are inherent to the version 3.3 used of *Vesta MAIS*. First, only a limited amount of heating technologies could be assessed, as other potential systems (e.g. medium-temperature heat networks, solar thermal, thermal energy from surface water, inclusion of storage options) are not included, only in the most recent 4.0 version of the model. A second issue found is that the model only allowed the implementation of ATES and HPs with very high building refurbishment, while in practice lower insulation levels may be sufficient (Brand & Svendsen, 2013). This may result in an overestimation of the refurbishment costs in the scenarios including these technologies. Similarly, we could argue that improving the building's shell with HTDH systems should be included among the potential options for a fair comparison between various plausible strategies.

The new investments required to decarbonize the existing CCGT heat network by shifting to sustainable heat sources (i.e. geothermal, biomass and waste heat of Table 3) were not possible to take into account in this research due to lack of available techno-economic data. Our study only considered the impact of decarbonizing the HTDH network in the calculation of the emission factors. This may have caused an underestimation of the costs in all the scenarios where the existing HTDH network is maintained. In the HTDH scenario, all areas would be affected by this issue. We can expect that the major impact originates from the investments in subtracting heat from geothermal sources, due to the large cost difference between geothermal DH and the current CCGT system (~ 1900 €/kW$_{th}$ and 165 €/kW$_{th}$ respectively) (Schepers & Leguijt, 2017). This effect, however, is likely to be limited when biomass and waste incineration plants replace the CCGT system, as cost differences between these systems are small. Nevertheless, it remains difficult to estimate the impact of this problem on the total costs, because of the numerous influencing factors, for instance, investments of geothermal plants can be up to ten times higher than those of CCGT, but variable and fixed costs are much smaller. Moreover, the required investments in the new heat source would only be partial, as in 8 of the 18 sub-neighbourhoods a HT distribution and transport network is already in place.

The following limitations are especially relevant for local practitioners applying *Vesta MAIS* to draw local heating strategies:

It can be claimed that the model results need to be refined with specific data representing more accurately the current circumstances and supported with local knowledge from urban planners as some input data is either based on national averages (e.g. potential of heat sources) or is not always up-to-date (e.g. insulation level of buildings, capacity of the electricity grid). Another constrain of the application of the model at local level is that costs are assessed from a system perspective. This can be valuable information during the first planning phase and as first assessment from a governmental point of view. However, for the decision-making of the involved actors in the heat supply chain, it is crucial to bring clarity how these costs can be allocated and what the ultimate impact per actor (e.g. end-user and heat companies) is. From the point of view of the building owner, having an estimation of the embedded costs required in the adoption of a new heating system or in the improvement of the building shell is highly important for the decision-making. Although this information would still represent averages and not necessarily apply to all individuals, this information can be crucial to policy makers to create the right instruments to further support the heat transition and to stimulate the cooperation among the involved stakeholders.

Our study looks at the performance of the various heating systems based on the quantity of energy without investigating the quality of energy from an exergetic point of view. This is important when comparing the exergy content of heat of various temperatures and power systems and understanding the impact on emissions. Electricity has intrinsically higher quality than heat while the exergy content of heat depends on aspects such as the temperature and pressure of the system. The quantification of exergy losses (which can be higher than the energy losses) of the various systems can help policy makers identify further energy improvement opportunities (Bilgen & Sarıkaya, 2015; Dincer, 2002). Despite the benefits of exergy analyses, this assessment could add another layer to an already complex issue for local governments and urban planners, which explains why the exergetic assessment of energy systems in buildings outside academia is uncommon (Sala Lizarraga and Picallo-Perez 2020).

Vesta MAIS appears as a valuable tool for an initial techno-economic assessment a local level. The model allows local governments and urban planners to make a first evaluation of the potential heating strategies in an area and compare them on basis of total costs and emissions. This aligns well with the objectives of the local governments in the Netherlands. However, it is important to emphasize that a certain technical and programming knowledge is needed to be able to adapt the model to the local situation, and thus, this might present a burden to local practitioners who lack this expertise.

Lastly, it is recommended that other factors, which are not integrated in the assessment of the present research but that are key for the assessment of heat strategies, are additionally assessed. Some examples are the reliability of the heat supply, the spatial constrains and the coupling opportunities of heating with other energy and urban plans.

Conclusions

This study has presented an approach to explore and identify sustainable heat strategies at the neighbourhood level and it aims to contribute to the existing methods used for local heat planning. At the moment of writing, it was the first attempt to apply the *Vesta MAIS* model at the neighbourhood level using a Dutch case study to assess a combination of various low-carbon heating technologies and insulation levels in buildings.

The results have demonstrated that for the majority of Overvecht, DH is a promising technology, with subtle underlying differences in the optimal levels of network temperature, heat density and building insulation between the different areas. Our findings show that LT electricity-based heating systems can reduce emissions by 75–80% against reference, while the decarbonization of the existing DH network can achieve up to 60% emission reductions. The average additional annualized system costs per home-equivalent compared to the reference vary between 86 and 414€ depending on the scenario. The highest annual system costs are observed for the HP scenario, followed by the ATES systems.

The sensitivity analysis revealed that the heat network, either HT or LT (i.e. ATES), is maintained as the preferred option for 17 of 18 sub-neighbourhoods, and the implementation of individual HPs remains the best alternative for the northern area where the heat demand density is low. The comparison of the LCOH of the individual technologies researched with published literature indicates a satisfactory performance of the approach used. Considering the economic competitiveness and better prospects offered by ATES systems, and generally LTDH over HTDH, such as the greater energy efficiency and the flexibility offered, the transition towards LT levels in DH networks seems a very logical pathway to take towards future-proof energy systems. Further research is recommended to understand the most optimal combination and synergies between network temperature and building insulation and to explore other key heating technologies such as medium-temperature DH networks and thermal energy from surface water, which are excluded in the present research.

As a recommendation for local policy makers, the *Vesta MAIS* model is suitable for a first techno-economic and CO_2 assessment of potential heat strategies at any neighbourhood or city. The outcomes of the model can be useful to sparkle the first discussions among the involved stakeholders and to provide perspectives for action. Nevertheless, the limitations identified by this study should be taken into account when applying the model for local decision-making on potential heat strategies. It is also suggested to look beyond techno-economic and CO_2 reduction criteria, by for example applying a multi-objective and multi-sector analysis, which can lead to a better understanding of the impacts of various strategies towards sustainable heating systems at local level.

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Author contribution Sara Herreras Martínez, Max Uytewaal: conceptualization, methodology, investigation, formal analysis, visualization and writing—original draft preparation. Robert Harmsen, Wen Liu: writing—reviewing and editing

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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